# Solar Activity and the Weather

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INSTITUTE FOR PLASMA RESEARCH
STANFORD UNIVERSITY, STANFORD, CALIFORNIA

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# SOLAR ACTIVITY AND THE WEATHER

John M. Wilcox
Institute for Plasma Research, Stanford University
Stanford, California 94305

## Abstract

The attempts during the past century to establish a connection between solar activity and the weather are discussed. Some critical remarks about the quality of much of the literature in this field are given. Several recent investigations are summarized. Use of the solar-interplanetary magnetic sector structure in future investigations is suggested to perhaps add an element of cohesiveness and interaction to these investigations.

# SOLAR ACTIVITY AND THE WEATHER

John M. Wilcox
Institute for Plasma Research, Stanford University,
Stanford, California 94305

"That there is a causal connection between the observed variations in the forces of the sun, the terrestrial magnetic field, and the meteorological elements has been the conclusion of every research into this subject for the past 50 years. The elucidation of exactly what the connection is and the scientific proof of it is to be classed among the most difficult problems presented in terrestrial physics. The evidence adduced in favor of this conclusion is on the whole of a cumulative kind, since the direct sequence of cause and effect is so far masked in the complex interaction of the many delicate forces in operation as to render its immediate measurement quite impossible in the present state of science. Before attempting to abstract the results of this research on these points a brief resume of the views held by the leading investigators will be given, especially with the object of presenting the status of the problem to those who are not fully acquainted with this line of scientific literature. The bibliography is large — covers a century — and embraces such names as...Gauss, Sabine,...Faraday, Wolf,...Stewart, Schuster,...Airy,...Kelvin, and many others." (Bigelow, 1898).

These words appear to provide a modern and contemporary introduction to an essay on solar activity and the weather, but in fact they were written 75 years ago. During this interval of 75 years, well over one thousand papers have been published on the subject. It may be fair, then, to ask exactly what has been accomplished.

An appreciable influence of solar activity on the weather is not widely accepted, and is not in every day use for forecasting purposes. The literature on the subject tends to be contradictory, and the work of the authors tends to be done in isolation. It is often very difficult to compare the claims of one author with those of another. Many times an author starts from scratch, rather than building on the work of his predecessors in the classical pattern of science. A widely accepted physical mechanism has not yet emerged.

Nevertheless, there are a few common threads that appear so widely in the otherwise disparate literature as to suggest that they probably have some validity. 1) Meteorological responses tend to occur two or three days after geomagnetic activity. 2) Meteorological responses to solar activity tend to be the most pronounced during the winter season. 3) Some meteorological responses over continents tend to be opposite from the responses over oceans.

Many scientists refuse to admit the possibility of an appreciable influence of solar activity on the weather in the absence of an accepted physical mechanism*. This viewpoint is to some extent valid, and we certainly will never rest until we understand the physical mechanisms involved. We may perhaps learn a lession from history at this point.

In his famous presidential address in 1892 to the Royal Society, Lord Kelvin said a few words regarding terrestrial magnetic storms and the hypothesis that they are due to magnetic waves eminating from the sun. He considered in particular the magnetic storm of June 25, 1885,

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*Such scientists presumably do not use aspirin.

and drew the following conclusions: "To produce such changes as these by any possible dynamical action within the sun, or in his atmosphere, the agent must have worked at something like 160 million, million, million, million horsepower (12 x $10^{35}$ ergs per second), which is about 364 times the total horsepower (3.3 x $10^{33}$ ergs per second) of the solar radiation. Thus, in this eight hours of a not very severe magnetic storm, as much work must have been done by the sun in sending magnetic waves out in all directions through space as he actually does in four months of his regular heat and light. This result, it seems to me, is absolutely conclusive (emphasis added) against the suposition that terrestrial magnetic storms are due to magnetic action of the sun; or to any kind of dynamical action taking place within the sun, or in connection with hurricanes in his atmosphere, or anywhere near the sun outside. It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sunspots is unreal, and that the seeming agreement between the periods has been a mere coincidence." (Kelvin, 1892).

These words of an eminent physicist, stated with the absolute assurance that has not completely deserted the profession today, were correct within the frame of reference in which they were uttered. What Lord Kelvin did not know about, and therefore did not take into account in his calculations, was of course the solar wind, which extended the sun's magnetic field lines out past the earth with the field strength decreasing less rapidly than $1/r^2$ rather than as $1/r^3$ as Lord Kelvin had assumed. We may ask today whether there may be an as yet unknown physical process related to solar activity and the weather that is comparable in importance and extent to the solar wind.

A meteorologist's opinion of the subject matter of this Symposium is given in the following quotation from Monin (1972):

> The greatest attention should be devoted to the question of whether there is a connection between the earth's weather and the fluctuations in solar activity. The presence of such a connection would be almost a tragedy for meteorology, since it would evidently mean that it would first be necessary to predict the solar activity in order to predict the weather; this would greatly postpone the development of scientific methods of weather prediction. Therefore, arguments concerning the presence of such a connection should be viewed most critically.

## INVESTIGATIONS OF THE EFFECT OF SOLAR ACTIVITY ON THE WEATHER

Having been unable to find in the voluminous literature a single coherent structure to describe and discuss in this paper, I shall proceed by citing a few recent reviews as sources for a bibliography, and then discuss a few recent representative investigations. Some recent reviews and discussions include Rubashev (1964), Schuurmans (1969), Markson (1971), Roberts and Olson (1973a) and Svalgaard (1973). A good cross-section of current activity in the field was given by the papers at the IUGG Symposium on "Solar Corpuscular Effects on the Stratosphere and Troposphere," Moscow, August 1971. The Symposium papers are in press. Fifty reports and communications were presented at the first All-Union Conference on the problem "Solar-Atmospheric Relationships in the Theory of Climate and Weather Forecasting" held in Moscow in 1972. A short description of this Conference is included as Appendix 1.

A prominent line of investigation during the past decade or longer has been led by W. O. Roberts with the participation of R. H. Olson, N. J. MacDonald, D. D. Woodbridge and T. W. Pohrte. I shall describe only the recent work of Roberts and Olson, but this, of course, has benefited from the earlier contributions. Roberts and Olson (1973b) have studied the development of 300 mb low pressure trough systems in the North Pacific and North America region. They find that troughs which enter (or are formed in) the Gulf of Alaska two to four days after a sharp rise of geomagnetic activity tend to be of larger than average size. In this investigation each trough is characterized by an objectively-derived vorticity area index, which is defined as the area of the trough for which the absolute vorticity $\geq 20 \times 10^{-5}\ \mathrm{sec}^{-1}$ plus the area $\geq 24 \times 10^{-5}\ \mathrm{sec}^{-1}$. The study included the winter half-years 1964-1971. Some results of this investigation are shown in Figure 1. During three to five days after the geomagnetic key day the troughs preceded by a sharp rise in geomagnetic activity have on the average about 40% larger vorticity area index than the troughs preceded by a geomagnetically quiet ten-day period. The statistical analysis given by these investigators appears to be compelling and to eliminate any probability of the result being associated with a statistical fluctuation.

The investigations of Roberts and Olson (1973b) were extended by Wilcox et al. (1973a). The vorticity area index was summed over the portion of the northern hemisphere north of $20^{\circ}$ N, and the time at which an interplanetary magnetic sector boundary was carried past the earth by the solar wind was used as the zero time in a superposed epoch analysis. We emphasize again that the sector boundary provides a well defined time, but that the meteorological response is associated with the large-scale sector structure during the interval of several days before and after the passing of the boundary, as discussed in more detail below. The results of the investigation shown in Figure 2 indicate that the vorticity area index reaches a minimum about one day after the passing of the sector boundary, followed by an increase of magnitude approximately 10% during the next two or three days. The result persists essentially unchanged as the list of sector boundary times is divided in two in three different ways. In a continuation of this investigation Wilcox et al. (1973b) found that the effect is present at all levels in the troposphere but only in the lowest portion of the stratosphere. The effect is not confined to a single interval of longitude or of latitude. Since this meteorological response is related to a well-defined solar structure it is not subject to the criticism of Hines (1973) discussed below.

Another prominent investigation during the past decade or longer is the work of E. R. Mustel (1972 and earlier work cited therein). Mustel has investigated the response of the ground level atmospheric pressure to geomagnetic moments based on the first day when an isolated geomagnetic storm becomes sufficiently strong. Mustel finds that in some regions of the globe the atmospheric pressure increases after the geomagnetic moment, whereas in other places the pressure decreases. The reaction time is about three days, and tends to increase with decreasing latitude. Figure 3 shows a representative result obtained by Mustel (1972) for the months December, January and February of the years 1890-1967. Large contiguous areas represented by the black circles have an increase in atmospheric pressure after geomagnetic disturbance, while other large areas represented by the open circles have a decrease. The mean statistical curves for the corresponding regions I, II, . . . are shown at the bottom of Figure 3.

Interplanetary magnetic field lines directed away from the sun can connect most readily with geomagnetic field lines directed into the northern polar cap, and interplanetary magnetic field lines directed toward the sun can connect most readily with geomagnetic field lines directed out of the southern polar cap. Thus in a given polar cap one might perhaps find changes in meteorological phenomena depending on the polarity of the interplanetary magnetic field. Mansurov et al. (1972) have found such an effect in the atmospheric pressure, using observations obtained during 1964. At a northern polar cap station (Mould Bay, near $80^{\circ}$ N) they found that the average pressure was higher when the interplanetary magnetic field was directed toward the sun, and at a conjugate southern polar cap station (Dumond d'Urville, near $80^{\circ}$ S) the average pressure was higher when the interplanetary magnetic field was directed away from the sun. Using only days in the first half of each interplanetary sector they obtained the results shown in the following table:

| | INTERPLANETARY FIELD | PRESSURE |
|---|---|---|
| NORTHERN POLAR STATION | AWAY | 1011.1 |
| | TOWARD | 1016.3 |
| SOUTHERN POLAR STATION | AWAY | 986.2 |
| | TOWARD | 982.7 |

When the entire interplanetary sectors were used (not just the first half of each) the same results were found, but the magnitude of the differences decreased. This is consistent with the observed properties of the interplanetary sector structure, because the average solar wind velocity and interplanetary field magnitude are larger in the first half of the sectors. The authors state that the results are valid with a statistical probability in excess of 99.5%.

Schuurmans (1969) has studied the influence of solar flares on the tropospheric circulation. The mean change in height of atmospheric constant pressure levels during the first 24 hours after a flare is greater than may be expected from mere random fluctuations in height. Average positive height changes are found to occur in the mid-latitude belts 45-65$^{\circ}$, while average negative height changes prevail poleward of 70$^{\circ}$ latitude. The maximum effect is found at approximately the 300 mb level and the effect appears to be stronger in winter than in the other seasons of the year. Significant mean height changes are found to occur only during the first 24 hours after a flare except at the ground level where significant changes do not appear until the third day after a flare. Schuurmans ascribes the causal agent to the corpuscular radiation of the flare rather than to UV radiation. A representative result is shown in Figure 4, showing that zonal averages of the pattern of 500 mb height changes as a function of latitude are approximately the same in the northern and the southern hemispheres.

Shapiro and Stolov (1972) have found significant increases in westerly winds at the 700 mb level in the longitude belt from 90$^{\circ}$ W to 180$^{\circ}$ approximately three or four days after magnetic storms. The effect results mainly from pressure falls in higher latitude (70$^{\circ}$ N) but also results partly from pressure rises at lower latitudes (20$^{\circ}$ N), and as usual is strongest in winter. Shapiro (1972) has also found a heightened persistence of sea level barametric pressure over North America and Europe in the first week after a geomagnetic storm, followed by decreased persistence in the second week.

Markson (1971) has studied thunderstorm activity as a function of the earth's position in a solar magnetic sector during 15 solar rotations in 1963 and 1964. The results shown in Figure 5 suggest a maximum in thunderstorm activity when the earth was at the leading edge of a sector with magnetic field directed toward the sun and at the trailing edge of a sector with magnetic field directed away from the sun, i.e. that thunderstorms maximized when the earth was crossing from an away sector into a toward sector. Bossolasco et al. (1972) have found that in the third and especially in the fourth day after the occurrence of an H$\alpha$ flare the global thunderstorm activity becomes higher than normal, increasing, on the average up to 50-70%, as shown in Figure 6. Reiter (1973) has found an increase in the frequency of influxes of stratospheric air masses down to 3 km after the occurrence of H$\alpha$ flares. This is detected through an increased concentration of the radionuclides BE7 and P32 at the measuring station at Zugspitze Peak in the Bavarian Alps. These radionuclides are preponderantly generated in the lower stratosphere. Some results are shown in Figure 7.

The largest meteorological response to solar activity occurs during winter. This is such a prominent and persistent feature in the literature that any magnetospheric or geomagnetic effects that show a large variation between winter and summer should be carefully considered in the search for physical mechanisms. For example, Berko and Hoffman (1973) have studied high-latitude field-aligned 2.3 keV electron precipitation data from OGO-4 at heights of approximately 800 km during the interval July 1967 through December 1968. This precipitation was found to occur primarily in a roughly oval-shaped region, with the greatest number of field-aligned events observed in the interval $67.5^{\circ} \leq$ magnetic latitude $\leq 72.5^{\circ}$ and 22 hours $\leq$ mean local time $\leq$ 01 hour. Figure 8 shows the probability of this 2.3 keV electron precipitation being field-aligned for the four seasons as a function of pitch angle. During winter this probability is more than twice the average value for all seasons. This result is interpreted by the authors in terms of a possible seasonal dependence in the altitude of double charge layers that may accelerate the electrons.

If other spacecraft experimenters could be encouraged to analyze their data in terms of the four seasons it seems possible that valuable clues to the physical mechanisms involved in the effects of solar activity on the weather might result.

The investigations described above represent a tiny fraction of the voluminous literature. I do not claim that they are necessarily the most significant. Indeed, it is quite clear that the most important papers on the subject of solar activity and the weather remain to be written. It appears reasonable to expect that the next few years may see more solid progress than has occurred in the previous 75 year interval.

## THE SOLAR-INTERPLANETARY MAGNETIC SECTOR STRUCTURE

Having criticized the existing literature as being fragmented, disconnected and unrelated, I would like to suggest a possible remedy. We should utilize the large advances in solar-terrestrial physics that have occurred during the past decade due to the advent of spacecraft, much improved ground-based observations, and the availability of large computers. A common organizing influence to which many of the existing investigations could be related is the solar and interplanetary magnetic sector structure. I will give a brief description of this structure, and then comment on its possible advantages for investigations of solar activity and the weather. The following discussion is taken from Wilcox et al. (1973b).

Figure 9 shows spacecraft observations of the polarity (away from or toward the sun) of the interplanetary magnetic field observed near the earth during two and one-half solar rotations. The plus (away) and minus (toward) signs at the periphery of the figure represent the field polarity during three-hour intervals. The four Archimedes spiral lines coming from the sun represent sector boundaries inferred from the spacecraft observations. Within each sector the polarity of the interplanetary field is predominantly in one direction. The interplanetary field lines are rooted in the sun, and so the entire field pattern rotates with the sun with an approximately 27-day period. The solar magnetic sector structure is extended outward from the sun by the radially flowing solar wind. The sector boundaries are often very thin, sometimes approaching a proton gyroradius in thickness. The time at which such boundaries are swept past the earth by the solar wind can therefore often be defined to within a fraction of an hour.

What would a sector boundary shown in Figure 9 look like on the visible solar disk? Wilcox and Howard (1968) have compared the interplanetary field observed by spacecraft near the earth with the solar photospheric magnetic field deduced from the longitudinal Zeeman effect measured at the 150-foot solar tower telescope at Mount Wilson Observatory. This analysis suggested that an average solar sector boundary is similar to the schematic shown in Figure 10. The boundary is approximately in the North-South direction over a wide range of latitudes on both sides of the equator. A large area to the right of the boundary has a large-scale field of one polarity and a large-scale region to the left of the boundary has a field of the opposite polarity.

Suppose we observe the mean solar magnetic field when the configuration is as shown in Figure 10. The mean solar magnetic field is defined as the average field of the entire visible solar disk, i.e., the field of the sun observed as though it were a star. In the circumstances shown in Figure 10, such an observation would yield a field close to zero, since there would tend to be equal and opposite contributions from the left and right sides of the figure. One day later the boundary will have rotated with the sun $13^{o}$ westward, and the visible disk will be dominated by the sector at the left in Figure 10. A mean field observation will now yield a field having the polarity appropriate to the dominant sector. This same polarity will be observed during several subsequent days, until the next sector boundary passes central meridian and reverses the polarity of the observed mean solar field.

Figure 11 shows a comparison of the mean solar field observed at the Crimean Astrophysical Observatory with the interplanetary magnetic field observed with spacecraft near the earth (Severny et al., 1970). In this comparison the mean solar field has been displaced by four and one-half days to allow for the average transit time from near the sun to the earth of the solar wind plasma that is transporting the solar field lines past the earth. We see in Figure 11 that in polarity and also to a considerable extent in magnitude the interplanetary field carried past the earth is very similar to the mean solar magnetic field. If we use the observed interplanetary field to investigate effects on the earth's weather, we are using a structure that is clearly of solar origin but is observed at precise times near the earth.

In addition to the sharp, well-defined change of polarity at the boundary, the sector structure has a large-scale pattern. During several days before a boundary is observed to sweep past the earth (or equivalently we may say during several tens of degrees of heliographic longitude westward of a boundary) conditions on the sun, in interplanetary space, and in the terrestrial environment tend to be quieter than average. Similarly after the boundary these conditions tend to be more active than average. A specific example of this is shown in Figure 12, which shows a superposed epoch analysis of the average effect on the geomagnetic activity index Kp as sector boundaries sweep past the earth. In the days before a boundary, the average geomagnetic activity has a monotonic decline to a minimum about one day before the boundary. Activity then rises to a peak a day or two after the boundary, and then resumes its decline (Wilcox and Colburn, 1972). The Van Allen radiation belts "breathe" inward and outward as the sector structure sweeps past the earth (Rothwell and Greene, 1966). Several other examples of the large-scale geomagnetic response to the sector structure have been given by Wilcox (1968). We emphasize that although the moment at which a sector boundary is carried past the earth provides a well-defined timing signal, the terrestrial effects are related for the most part to the large-scale structure existing for several days on each side of the boundary.

From the above discussion, it appears reasonable to use the solar magnetic sector structure in an investigation of possible effects on the earth's weather. The use of the sector structure for this purpose has several advantages. We are using a fundamental large-scale property of the sun. There can then be no doubt that any observed atmospheric response to the passing of a sector boundary is ultimately caused by the solar magnetic sector structure. We emphasize that "solar magnetic sector structure" is a name for the entire structure discussed above. When we say that an atmospheric response is caused by the solar magnetic sector structure, we include possibilities that the effect has been transmitted through interplanetary space in the form of magnetic fields, solar wind plasma, energetic particles or radiation. Similarly, an atmospheric effect observed in the troposphere may flow through the higher atmospheric layers in an exceedingly complex manner.

We discuss some further advantages of the sector structure for such investigations. In the sense discussed above, a tropospheric response does not have its ultimate cause in other atmospheric processes. Some earlier investigations of solar activity and the weather have been criticized in this respect by Hines (1973). Because of the four or five day transit time of the solar wind plasma from the sun to the earth, we can have, by observing the mean solar magnetic field, a four or five day forecast of the time at which a sector boundary will sweep past the earth.

By improving the solar observation procedure, we may be able to detect a sector boundary two or three days after it has rotated past the eastern limb of the sun. This would add an additional four or five days to the forecast interval.

From one solar rotation to the next, the sector structure usually does not change very much. In the course of a year there are often significant changes in the sector structure, which appears to have significant variations through the 11-year sunspot cycle (Svalgaard, 1972). All of these regularities and recurrence properties may be of significant assistance in forecasting. As the solar magnetic sector structure and its interplanetary and terrestrial consequences become better understood in the coming years, the possibilities of using solar data in weather forecasting should also improve.

A list of observed and well-defined sector boundaries is given in Appendix 2. If it were possible for investigators in this field to agree on the use of this list for at least one small part of their investigations, an important element of cohesiveness and interaction might be added to the literature.

Having started with a quotation from Bigelow written in 1898, I would like to end with a quotation from E. N. Parker from the Calgary Conference on Solar Terrestrial Relations in 1972:

> The information on hand indicates a strong and important connection between geomagnetic activity and weather. So if the statistics need improving, let us improve them through further studies. If a physical connection is missing, then we have before us the fascinating task of discovering it. Then perhaps in a few years we can bring a significant improvement to the forecasting of weather in the populated areas of Canada and the United States. We may suppose that a similar connection between geomagnetic activity and the formation of storms exists in other parts of the world too. And can be discovered if sought after."

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Figure Captions

Figure 1. Mean vorticity area index for troughs preceded by sharp geomagnetic activity increases and for troughs preceded by a 10-day geomagnetically quiet period. (For the key troughs add 3 days, on the average, to the lags shown in order to ascertain the number of days since the geomagnetic rise that led to the designation as a key trough.) (Roberts and Olson, 1973b).

Figure 2. Average response of the vorticity area index to the solar magnetic sector structure. Sector boundaries were carried past the earth by the solar wind on day 0. The analysis includes 54 boundaries during the winter months November to March in the years 1964 to 1970. The boundaries were divided into two parts according to (a) the magnetic polarity change at the boundary, (b) the first or last half of winter, and (c) the yearly intervals 1964 to 1966 and 1967 to 1970. (a) The dotted curve represents 24 boundaries in which the interplanetary magnetic field polarity changed from toward the sun to away, and the dashed curve 30 boundaries in which the polarity changed from away to toward. (b) The dotted curve represents 32 boundaries in the interval 1 November to 15 January, and the dashed curve 22 boundaries in the interval 16 January to 31 March. (c) The dotted curve represents 26 boundaries in the interval 1964 to 1966, and the dashed curve 28 boundaries in the interval 1967 to 1970. The curves have been arbitrarily displaced in the vertical direction,

each interval on the ordinate axis being $5 \times 10^5$ km$^2$ (Wilcox et al., 1973).

Figure 3. Hemispheric distribution of the change of atmospheric pressure after a geomagnetic storm for the months December through February and the years 1890-1967. The black circles correspond to an increase in pressure and the open circles to a decrease in pressure. At the bottom of the figure the mean statistical curves for the regions I, II, . . . are given (Mustel, 1972).

Figure 4. Zonal averages of the difference in height of the 500 mbar level between the first aerological observation after a flare and the observation 24 hours earlier as a function of latitude for both hemispheres (Schuurmans, 1969).

Figure 5. Thunderstorms as a function of the earth's position in a solar sector: negative sectors (top curve); positive sectors (bottom curve); transitions to adjacent sectors of opposite sign seen at days 0 and 8; all points shown to indicate variance in data; curves drawn through locus of points closest to each daily increment of time; numbers in points give days in sector being normalized, i.e., each point is average for all sectors of that length at that increment of the sector's length (Markson, 1971).

Figure 6. Superposed-epoch analysis of the thunderstorm activity before and after H$\alpha$ flare day (with H$\alpha$ flare day as a key-day). Data are expressed in terms of percentage differences from the value corresponding to the key-day: a) = 1961-1965,

b) = 1966-1970, c) = 1961-1970 (Bossolasco et al., 1972).

Figure 7. Superposed epoch analysis of Be7 and P32 concentrations in air at 3 km a.s.l. and various solar and geophysical data; key days (n): solar H flares of different intensity and solar positions; vertical bars: standard deviation (Reiter, 1973).

Figure 8. Probability of 2.3 keV electron precipitation being field-aligned for the four seasons as a function of pitch angle in the mean local time interval 22 hours to 01 hour. The seasons are defined as equal time intervals around the equinoxes and the solstices. During winter the probability is more than twice as large as the average for all seasons (Berko and Hoffman, 1973).

Figure 9. The inner portion of the figure is a schematic representation of a sector structure of the interplanetary magnetic field that is suggested by observations obtained with the IMP-1 spacecraft in 1963. The plus signs (away from the sun) and minus signs (toward the sun) at the circumference of the figure indicate the direction of the measured interplanetary magnetic field during successive 3-hour intervals. The deviations about the average streaming angle that are actually present are not shown (Wilcox and Ness, 1965).

Figure 10. Schematic of an average solar sector boundary. The boundary is approximately in the North-South direction over a wide range of latitude. The solar region to the west of the boundary is unusually quiet and the region to the east of the boundary is unusually active (Wilcox, 1971).

Figure 11. Comparison of the magnitude of the mean solar field and of the interplanetary field. The open circles are the daily observations of the mean solar field, and the dots are 3-hour average values of the interplanetary field magnitude observed near the earth. The solar observations are displaced by $4\frac{1}{2}$ days to allow for the average sun-earth transit time. The abscissa is the time of the interplanetary observations (Severny et al., 1970).

Figure 12. Superposed epoch analysis of the magnitude of the planetary magnetic 3-hour range indices Kp as a function of position with respect to a sector boundary. The abscissa represents position with respect to a sector boundary, measured in days, as the sector pattern sweeps past the earth (Wilcox and Colburn, 1972).

## APPENDIX 1

### Conference on Solar-Atmospheric Relationships

The first All-Union Conference on the Problem "Solar-Atmospheric Relationships in the Theory of Climate and Weather Forecasting" was held recently in Moscow. It was called on the initiative of the Main Administration of the Hydrometeorological Service of the USSR Council of Ministers. Scientific specialists from the USSR Hydrometeorological Center, Main Astronomical Observatory USSR Academy of Sciences, Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation USSR Academy of Sciences, Main Geophysical Observatory, Arctic and Antarctic Scientific Research Institute, Central Aerological Observatory, Institute of Biology of Internal Waters USSR Academy of Sciences, Marine Hydrophysical Institute Academy of Sciences Ukrainian SSR, Institute of Applied Geophysics, and Leningrad and Kazan' State Universities, as well as the Advanced Marine Engineering Institute imeni Admiral S. O. Makarov, the Scientific Research Heliometeorological Station Gornaya Shoriya and the Kherson Agrometeorological Station, presented different reports at its sessions.

Fifty reports and communications were presented at the conference, which lasted 3 days. Representatives of different scientific research institutes and laboratories participated in their discussion.

In a lengthy resolution the conference noted that investigations of different aspects of the "Sun-Earth's Atmosphere" problem investigated over a period of several decades in the USSR and abroad make it possible to assert with assurance that solar activity and other space-geophysical factors exert a substantial influence on atmospheric processes. Allowance for these factors is of great importance in preparing weather forecasts.

It was noted at the conference that the Soviet scientists M. S. Eygenson, V. Yu. Vize, L. A. Vitel's, B. M. Rubashov, A. I. Ol', I. V. Maksimov, A. A. Girs, T. V. Pokrovskaya, M. N. Gnevyshev, A. V. D'yakov, P. P. Predtechenskiy, E. R. Mustel' and R. F. Usmanov have made a substantial contribution to study of these problems. Many interesting and promising investigations have been made by the younger generation of scientists.

While noting the considerable attainments of Soviet science in solving the problem of solar-terrestrial relationships, and in taking into account their role in the practical activity of the USSR Hydrometeorological Service, the conference nevertheless pointed out serious shortcomings.

For example, in the USSR Hydrometeorological Service and in the USSR Academy of Sciences there is still no organization for coordinating and planning work of solar specialists or for putting into practice the results already achieved by them. We have not properly organized the collection, processing and routine use of solar and geophysical information in weather forecasting work. As a result, in the development and improving of forecasting methods allowance is unfortunately not made for the role of solar-atmospheric relationships; they are usually ignored when preparing weather forecasts by synoptic and numerical methods.

Accordingly, the conference deemed it desirable to broaden work on the study of the influence of a complex of space-geophysical factors on the atmosphere and weather, one of the most important problems facing the USSR Hydrometeorological Service. The conference has laid out a broad program of investigations, for these purposes using the latest instruments, rockets, space vehicles, electronic computers, etc.

In the conference's resolution it was especially noted that there must be the fastest possible training of highly skilled specialists on the problem "Sun-Lower Atmosphere" through the graduate school level; there is also an urgent need for organizing annual courses on heliometeorology for workers in scientific, academic and operational units of the USSR Hydrometeorological Service.

Beginning with 1973 plans call for publication of specialized collections of articles on heliometeorology and broadening of publication of materials on solar-terrestrial relationships in the journals Meteorologiya i Gidrologiya and Fizika Atmosfery i Okeana. The Hydrometeorological Center USSR, Main Geophysical Observatory and Arctic and Antarctic Institute have been delegated the task of generalizing investigations on this problem and preparing a systematic manual for operational workers in the USSR weather forecasting service.

The conference deems it desirable to create in the key institutes of the Hydrometeorological Service a network of heliometeorological stations (observatories) and at some universities and hydrometeorological institutes -- departments of solar-terrestrial relationships. Solar specialists expect great assistance from the institutes of the USSR Academy of Sciences and the academies of science of some union republics, particularly in the plan for forecasting solar activity.

Considering the results of the First All-Union Conference, it has been decided to issue a collection of articles by its participants and in the future to hold such conferences regularly, each 2 or 3 years, and in the time intervals between them to hold working conferences on individual aspects of the problem.

In its resolution the conference especially noted the positive role which was played by discussion of the problem of solar-terrestrial relationships and their prediction on the pages of the newspapers Sel'skaya Zhizn', Pravda, and Literaturnaya Gazeta (June-October 1972). The questions raised in the press and the critical comments made by the newspapers have favored a broader discussion of this problem and its role in weather forecasting.

The conference was concluded by words from Academician Ye. K. Fedorov, chief of the Main Administration of the Hydrometeorological Services of the USSR Council of Ministers.
(Excerpts: "Sun, Climate, Weather," by B. Lesik; Moscow, Sel'skaya Zhizn' 11 November 1972, p 2)

## Appendix 2

List of observed and well-defined sector boundaries.

The date, sign change (+ away, - toward), and time (in 3-hour intervals) is given for all observed sector boundaries with at least four days of opposite field polarity on each side of the boundary. The notation 8-1 means that the boundary occurred between the last 3-hour interval of that day and the first 3-hour interval of the next day.

OBSERVED AND WELL-DEFINED SECTOR BOUNDARIES

| Year | Day of Year | Sign | Date | Time | |
|---|---|---|---|---|---|
| 1962 | 253 | +, - | September 10 | 8-1 | |
| | 269 | -, + | September 26 | 3-4 | |
| | 281 | +, - | October 8 | 4-5 | |
| | 293 | -, + | October 20 | 8-1 | |
| 1963 | 336 | -, + | December 2 | 8-1 | |
| | 346 | +, - | December 12 | 4-3 | (gap) |
| | 354 | -, + | December 20 | 1-2 | |
| 1964 | 007 | +, - | January 7 | 7-8 | |
| | 016 | -, + | January 16 | 2-2 | (gap) |
| | 023 | +, - | January 23 | 3-4 | |
| | 035 | +, - | February 4 | 2-3 | |
| | 284 | -, + | October 10 | 6-7 | (1 day gap) |
| | 291 | +, - | October 17 | 7-8 | |
| | 297 | -, + | October 23 | 6-8 | (1 day gap) |
| | 306 | +, - | November 1 | 5-6 | |
| | 312 | -, + | November 7 | 2-1 | (gap) |
| | 320 | +, - | November 15 | 5-6 | |
| | 325 | -, + | November 20 | 3-2 | (gap) |
| | 332 | +, - | November 27 | 7-8 | |
| | 341 | -, + | December 6 | 4-5 | |
| | 345 | +, - | December 10 | 8-1 | |
| | 349 | -, + | December 14 | 8-1 | |
| | 361 | +, - | December 26 | 1-2 | |
| 1965 | 002 | -, + | January 2 | 1-2 | |
| | 008 | +, - | January 8 | 1-2 | |
| | 012 | -, + | January 12 | 2-3 | |
| | 032 | +, - | February 1 | 8-1 | |
| | 125 | +, - | May 5 | 4-5 | |
| | 153 | +, - | June 2 | 8-1 | |
| | 161 | -, + | June 10 | 2-3 | |
| | 230 | -, + | August 18 | 7-6 | (gap) |
| | 235 | +, - | August 23 | 5-7 | (gap) |
| | 259 | -, + | September 16 | 2-3 | |

OBSERVED AND WELL-DEFINED SECTOR BOUNDARIES

| Year | Day of Year | Sign | Date | Time | |
|---|---|---|---|---|---|
| 1966 | 001 | +, - | January 1 | 6-7 | (1 day gap) |
| | 032 | +, - | February 1 | 4-5 | |
| | 043 | -, + | February 12 | 2-3 | |
| | 062 | +, - | March 3 | 3-4 | |
| | 067 | -, + | March 8 | 2-3 | |
| | 089 | +, - | March 30 | 2-3 | |
| | 099 | -, + | April 9 | 1-2 | |
| | 127 | -, + | May 7 | 8-1 | |
| | 249 | -, + | September 6 | 5-6 | |
| | 257 | +, - | September 14 | 6-7 | |
| | 276 | -, + | October 3 | 6-7 | |
| | 285 | +, - | October 12 | 2-3 | |
| | 303 | -, + | October 30 | 5-6 | |
| | 312 | +, - | November 8 | 4-5 | |
| | 331 | -, + | November 27 | 7-8 | |
| | 338 | +, - | December 4 | 3-4 | |
| 1967 | 001 | +, - | January 1 | 7-8 | |
| | 013 | +, - | January 13 | 3-4 | |
| | 018 | -, + | January 18 | 2-3 | (1 day gap) |
| | 081 | -, + | March 22 | 7-8 | |
| | 216 | -, + | August 4 | 5-6 | |
| | 242 | -, + | August 30 | 2-3 | (1 day gap) |
| | 249 | +, - | September 6 | 6-7 | |
| | 270 | -, + | September 27 | 3-4 | |
| | 276 | +, - | October 3 | 1-2 | |
| | 297 | -, + | October 24 | 2-3 | |
| | 324 | -, + | November 20 | 4-5 | |
| | 338 | +, - | December 4 | 5-6 | |
| 1968 | 001 | +, - | January 1 | 6-5 | (gap) |
| | 028 | +, - | January 28 | 8-1 | |
| | 042 | -, + | February 11 | 3-4 | |
| | 057 | +, - | February 26 | 6-7 | |
| | 070 | -, + | March 10 | 4-5 | |
| | 083 | +, - | March 23 | 5-6 | |
| | 096 | -, + | April 5 | 7-8 | |
| | 112 | +, - | April 21 | 3-4 | |
| | 123 | -, + | May 2 | 1-2 | |
| | 138 | +, - | May 17 | 5-6 | |
| | 185 | -, + | July 3 | 3-4 | |
| | 191 | +, - | July 9 | 8-1 | |
| | 199 | -, + | July 17 | 4-5 | |
| | 207 | +, - | July 25 | 4-5 | |
| | 213 | -, + | July 31 | 7-8 | |
| | 226 | -, + | August 13 | 7-8 | |

OBSERVED AND WELL-DEFINED SECTOR BOUNDARIES

| Year | Day of Year | Sign | Date | Time | |
|---|---|---|---|---|---|
| 1968 (cont.) | 234 | +, - | August 21 | 2-3 | |
| | 263 | +, - | September 19 | 2-3 | |
| | 290 | +, - | October 16 | 5-6 | |
| | 318 | +, - | November 13 | 2-3 | |
| | 334 | -, + | November 29 | 6-8 | (gap) |
| | 345 | +, - | December 10 | 2-3 | |
| | 359 | -, + | December 24 | 6-7 | |
| 1969 | 006 | +, - | January 6 | 5-6 | |
| | 023 | -, + | January 23 | 8-1 | |
| | 033 | +, - | Feburary 2 | 5-6 | |
| | 050 | -, + | February 19 | 2-3 | |
| | 090 | +, - | March 31 | 6-7 | |
| | 110 | -, + | April 20 | 7-1 | (gap) |
| | 119 | +, - | April 29 | 3-4 | |
| | 127 | -, + | May 7 | 6-3 | (gap) |
| | 132 | +, - | May 12 | 8-2 | (gap) |
| | 138 | -, + | May 18 | 6-7 | |
| | 147 | +, - | May 27 | 1-2 | |
| | 165 | -, + | June 14 | 3-4 | |
| | 192 | -, + | July 11 | 2-3 | |
| | 202 | +, - | July 21 | 5-6 | |
| | 219 | -, + | August 7 | 6-7 | |
| | 248 | -, + | September 5 | 3-4 | |
| | 303 | -, + | October 30 | 8-1 | |
| | 330 | -, + | November 26 | 5-6 | |
| | 343 | +, - | December 9 | 1-2 | |
| | 356 | -, + | December 22 | 7-8 | |
| 1970 | 040 | -, + | February 9 | 7-8 | |
| | 067 | -, + | March 8 | 8-1 | |
| | 120 | -, + | April 30 | 3-4 | |
| | 131 | +, - | May 11 | 6-7 | |
| | 158 | +, - | June 7 | 6-7 | |
| | 243 | +, - | August 31 | 8-5 | (gap) |
| | 309 | -, + | November 5 | 3-4 | |
| | 328 | +, - | November 24 | 3-4 | |

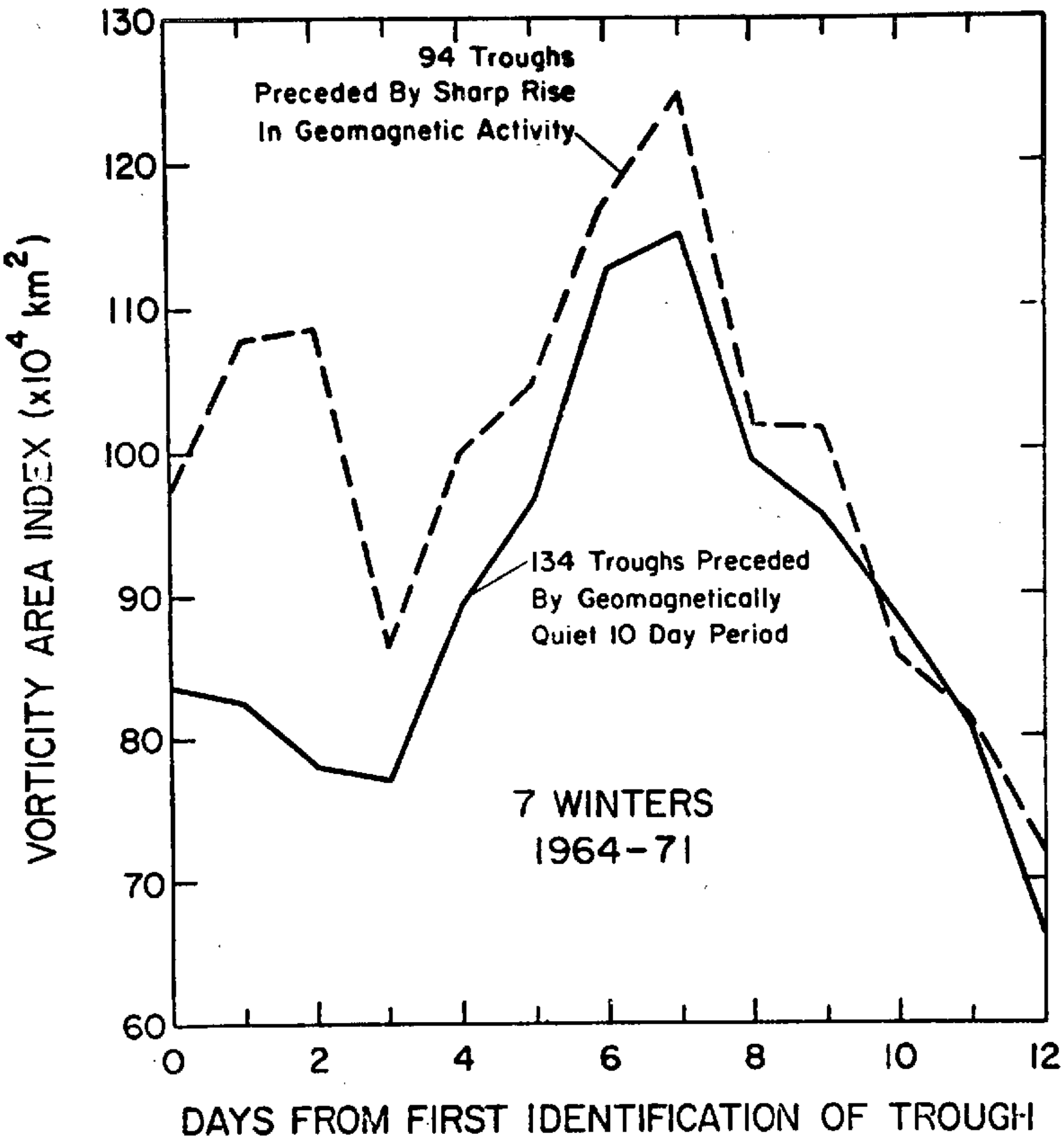

94 Troughs
Preceded By Sharp Rise
In Geomagnetic Activity
134 Troughs Preceded
By Geomagnetically
Quiet 10 Day Period
7 WINTERS
1964-71
VORTICITY AREA INDEX ($\times 10^4\ km^2$)
DAYS FROM FIRST IDENTIFICATION OF TROUGH
130
120
110
100
90
80
70
60
0
2
4
6
8
10
12

Figure 1

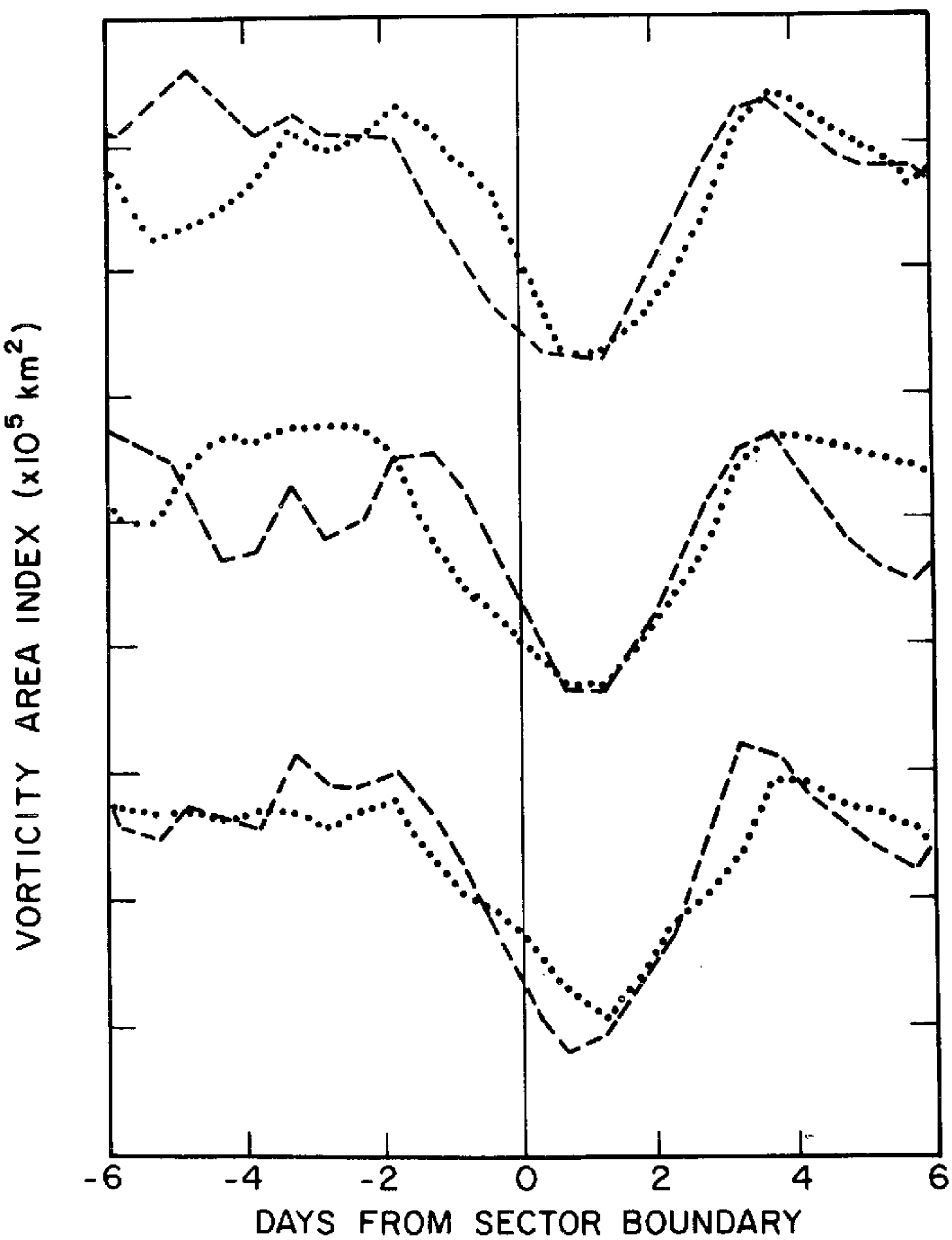

VORTICITY AREA INDEX (x10$^5$ km$^2$)
-6
-4
-2
0
2
4
6
DAYS FROM SECTOR BOUNDARY

Figure 2

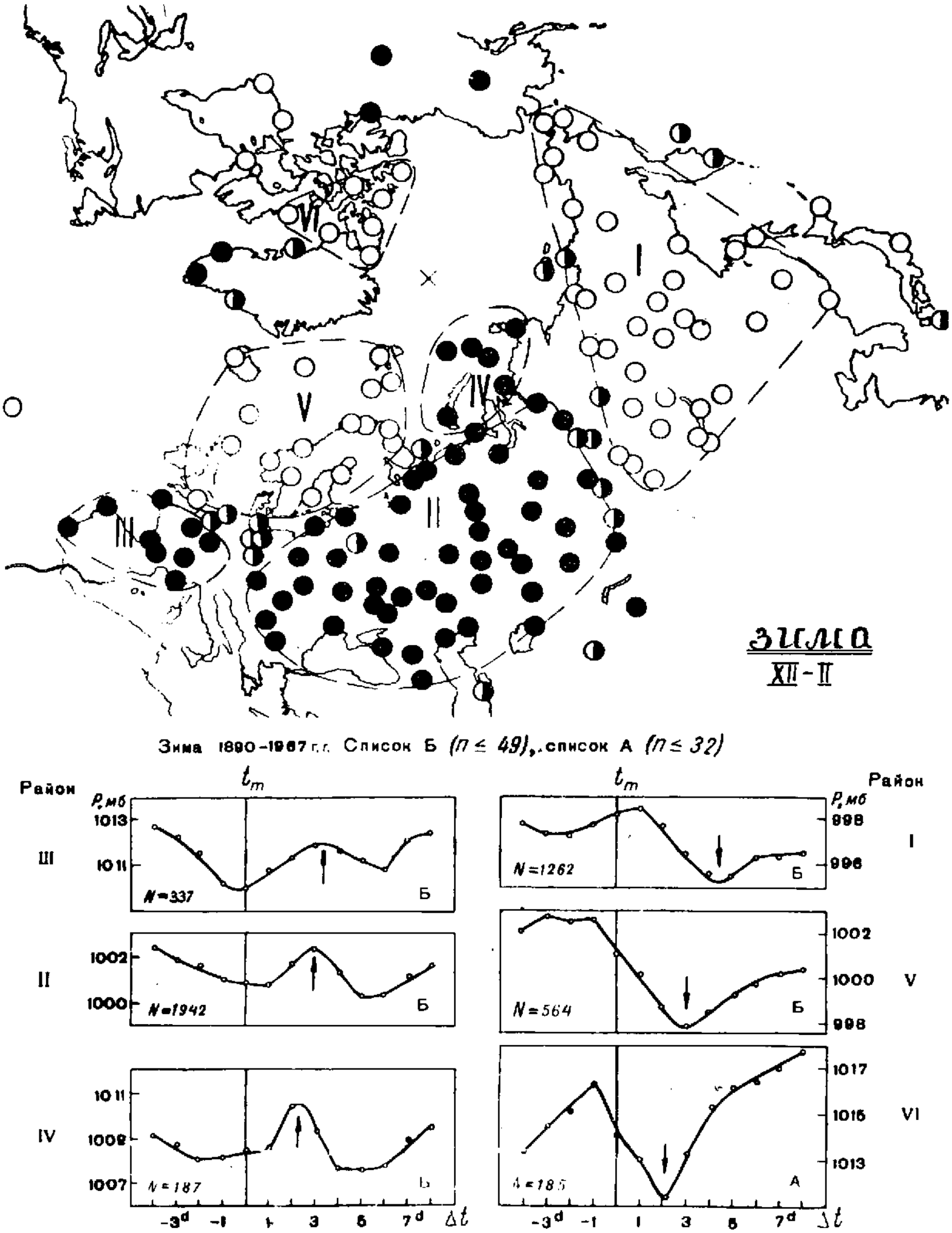
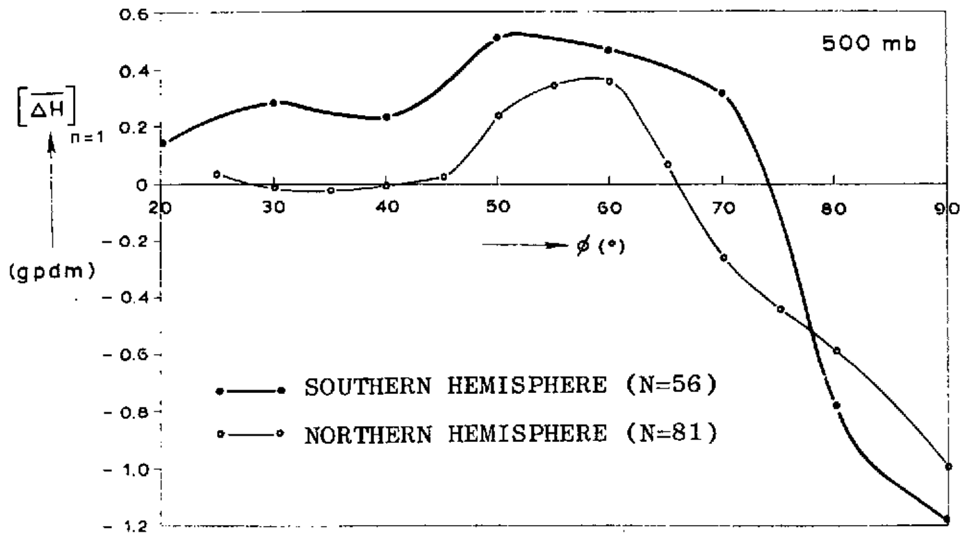
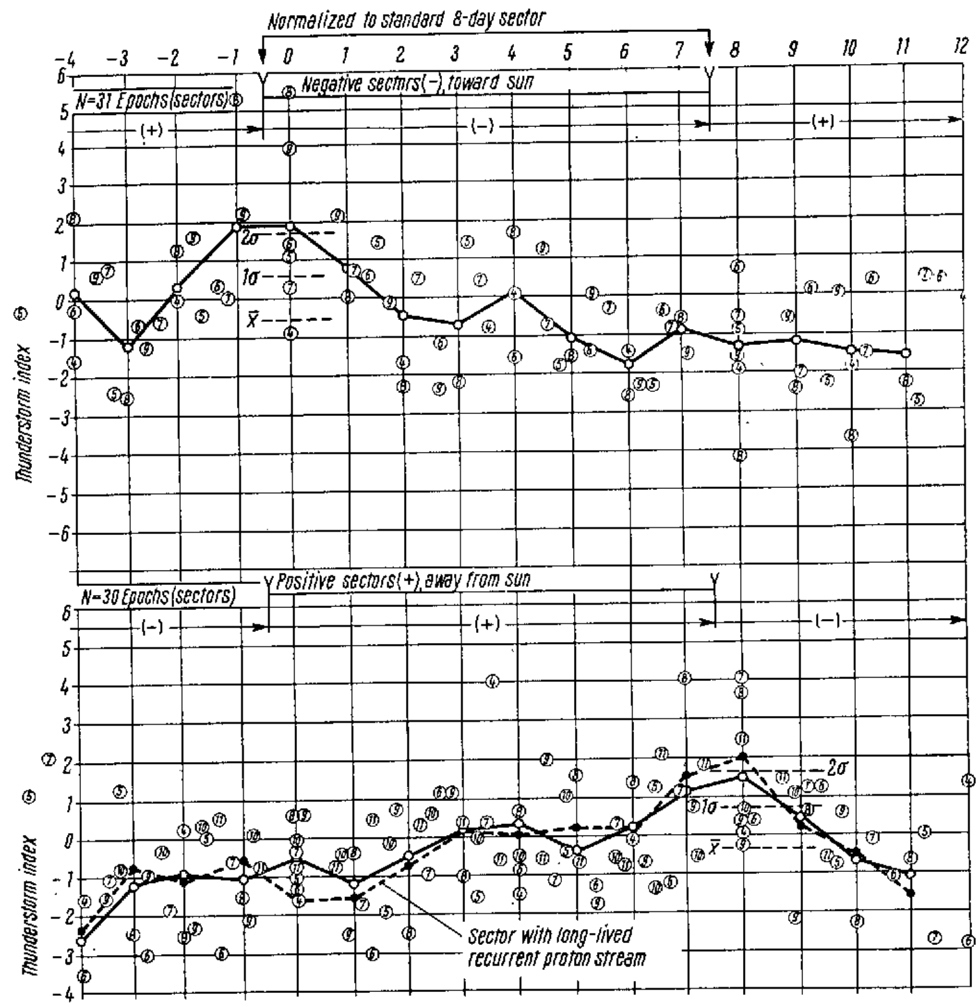

Зима
XII - II
Зима 1890-1967 г.г. Список Б ($n \le 49$), список А ($n \le 32$)
Район
$t_m$
Р, мб
III
II
IV
I
V
VI
N=337
N=1942
N=187
N=1262
N=564
Б
А
$\Delta t$

Figure 3



0.6
0.4
0.2
0
- 0.2
- 0.4
- 0.6
- 0.8
- 1.0
- 1.2
[ΔH] n=1
(gpdm)
20
30
40
50
60
70
80
90
φ (°)
500 mb
SOUTHERN HEMISPHERE (N=56)
NORTHERN HEMISPHERE (N=81)


Figure 4



Normalized to standard 8-day sector
Negative sectors(−), toward sun
N=31 Epochs(sectors)
Positive sectors(+), away from sun
N=30 Epochs(sectors)
Thunderstorm index
Sector with long-lived recurrent proton stream


**Figure 5**

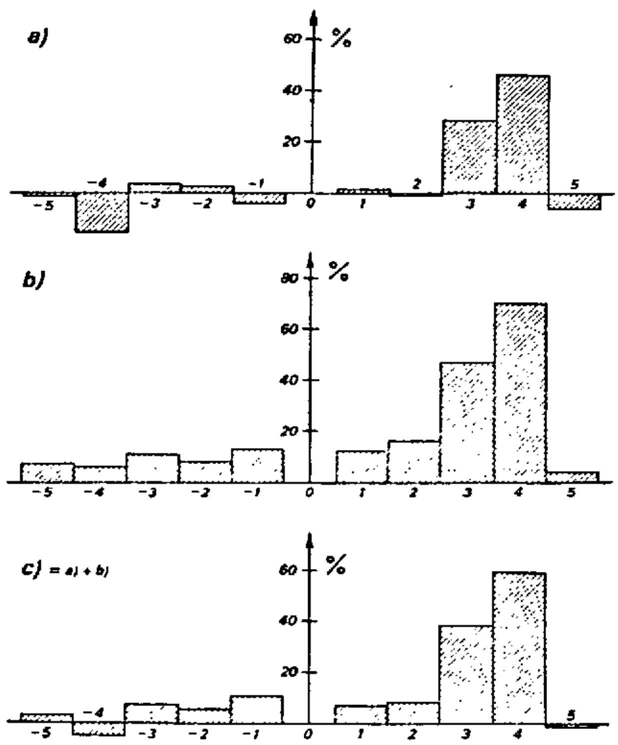
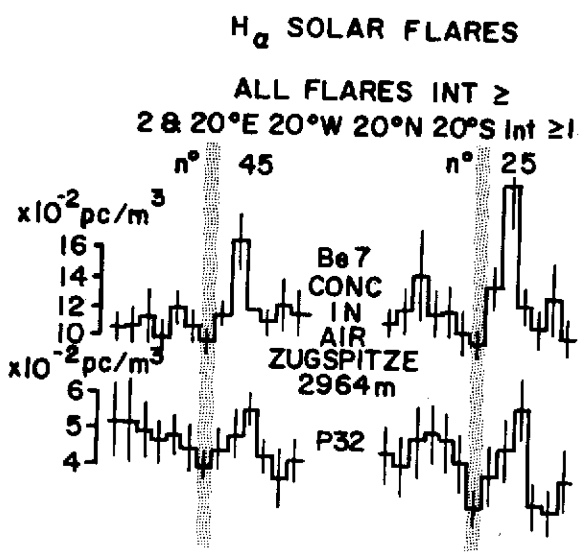
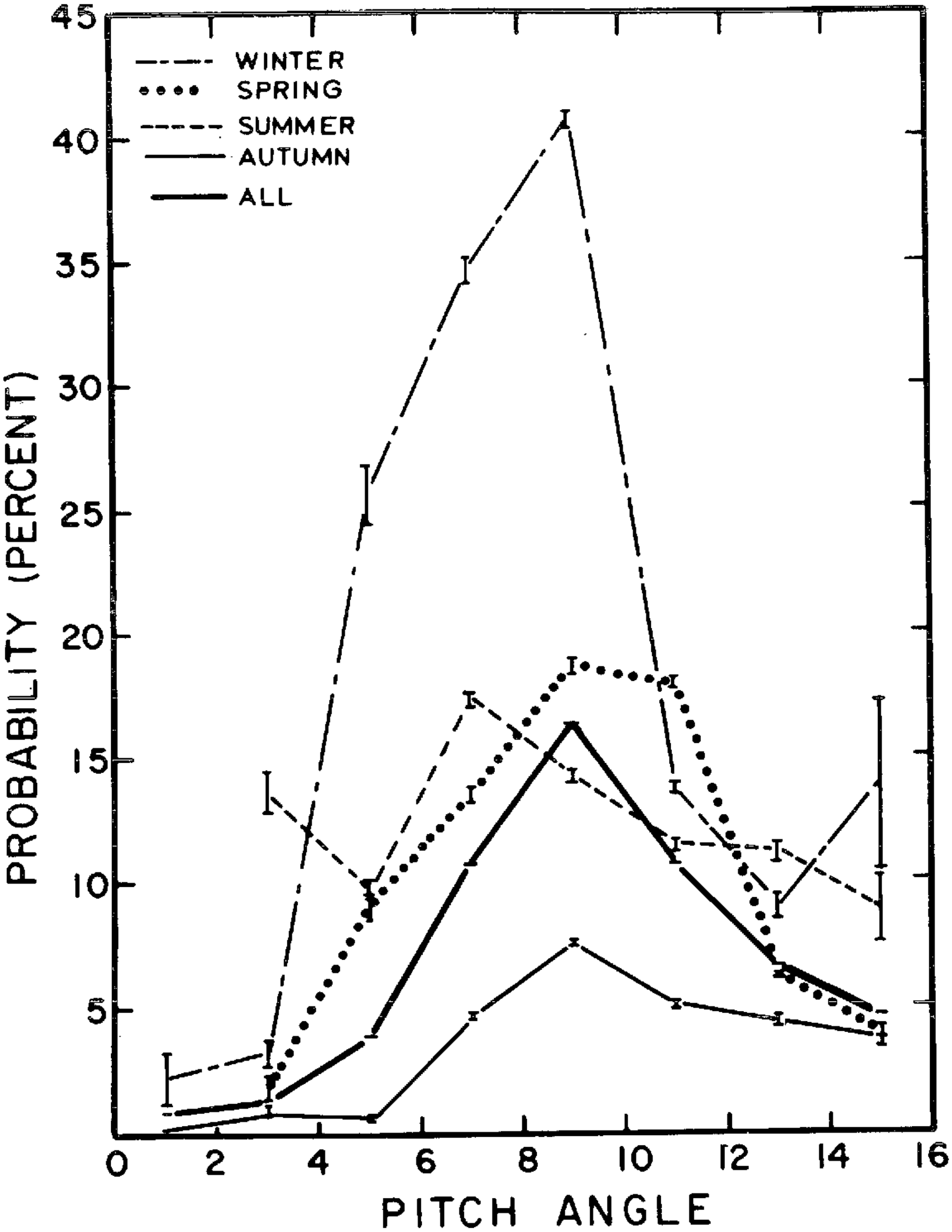

a)
%
60
40
20
-5
-4
-3
-2
-1
0
1
2
3
4
5
b)
%
80
60
40
20
-5
-4
-3
-2
-1
0
1
2
3
4
5
c) = a) + b)
%
60
40
20
-5
-4
-3
-2
-1
0
1
2
3
4
5

Figure 6



$H_\alpha$ SOLAR FLARES
ALL FLARES INT ≥
2 & 20°E 20°W 20°N 20°S Int ≥1
n° 45
n° 25
$\times 10^{-2}$ pc/$m^3$
16
14
12
10
Be 7
CONC
IN
AIR
ZUGSPITZE
2964 m
$\times 10^{-2}$ pc/$m^3$
6
5
4
P32


Figure 7



WINTER
SPRING
SUMMER
AUTUMN
ALL
PROBABILITY (PERCENT)
45
40
35
30
25
20
15
10
5
0
2
4
6
8
10
12
14
16
PITCH ANGLE


Figure 8

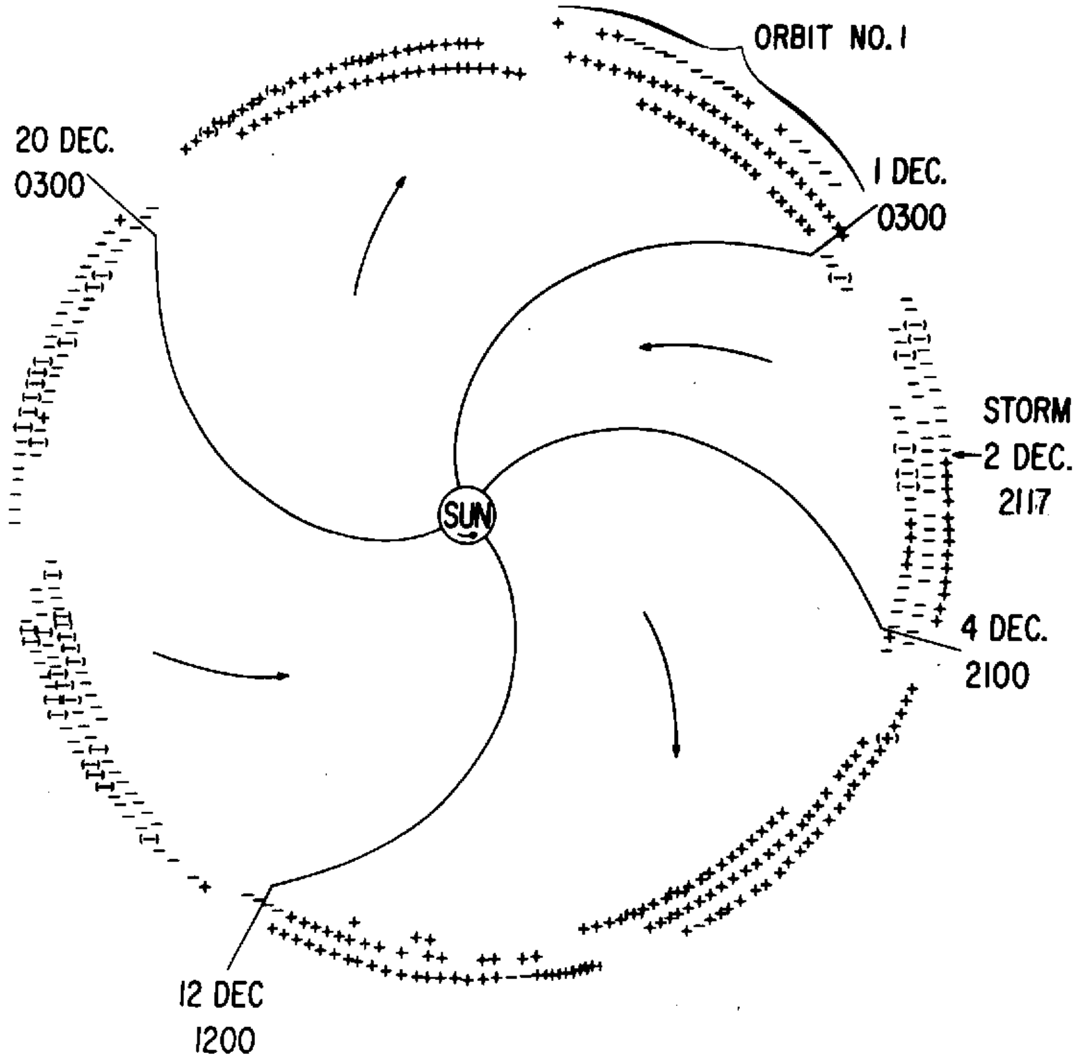

ORBIT NO. 1
1 DEC.
0300
STORM
2 DEC.
2117
4 DEC.
2100
12 DEC
1200
20 DEC.
0300
SUN

Figure 9

## SCHEMATIC OF SOLAR SECTOR BOUNDARY

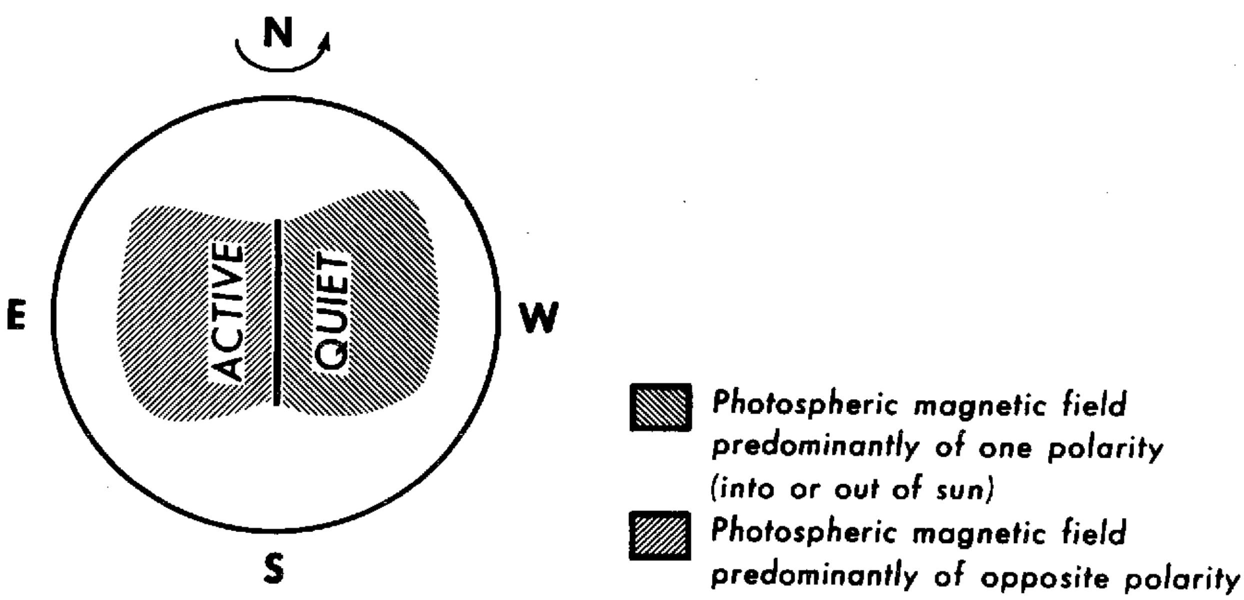



Figure 10

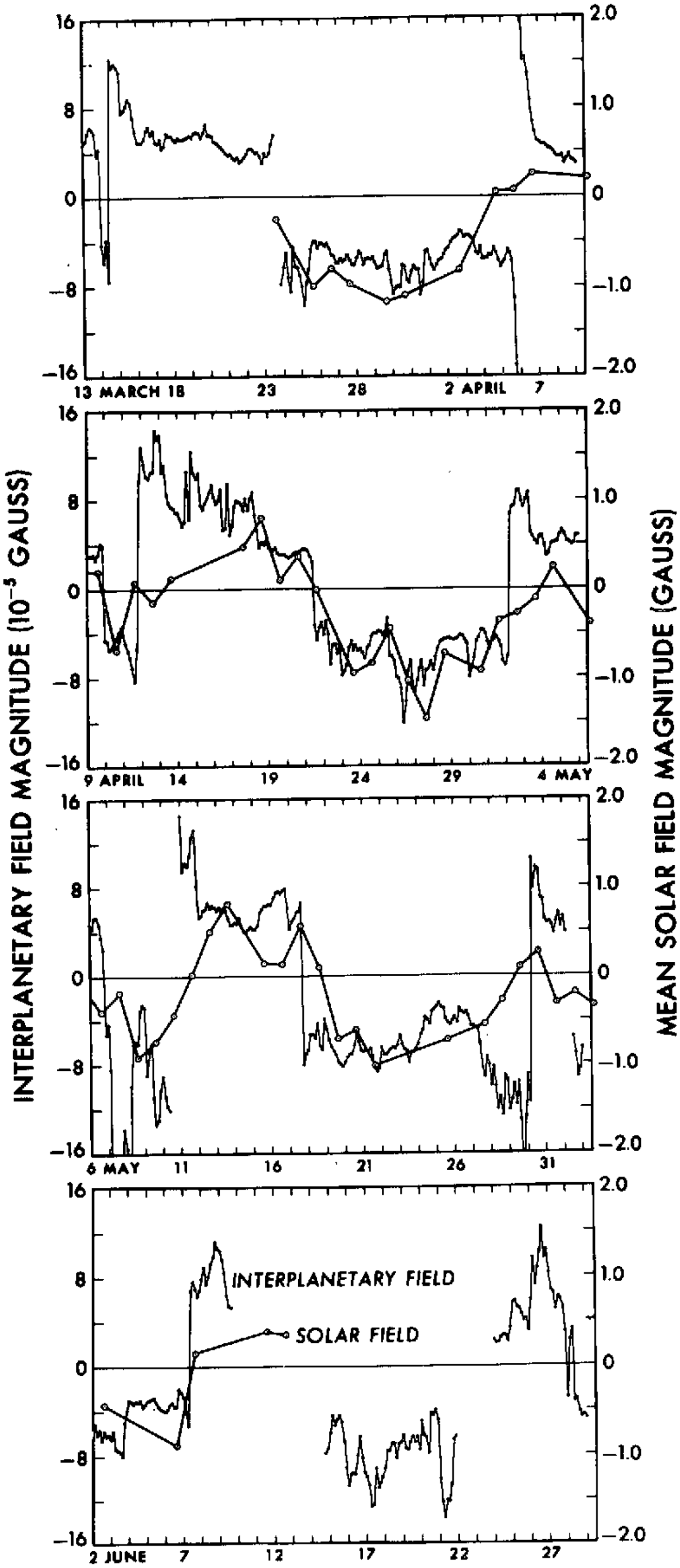

INTERPLANETARY FIELD MAGNITUDE ($10^{-5}$ GAUSS)
MEAN SOLAR FIELD MAGNITUDE (GAUSS)
16
8
0
-8
-16
2.0
1.0
0
-1.0
-2.0
13 MARCH 18
23
28
2 APRIL
7
9 APRIL
14
19
24
29
4 MAY
6 MAY
11
16
21
26
31
2 JUNE
7
12
17
22
27
INTERPLANETARY FIELD
SOLAR FIELD

Figure 11

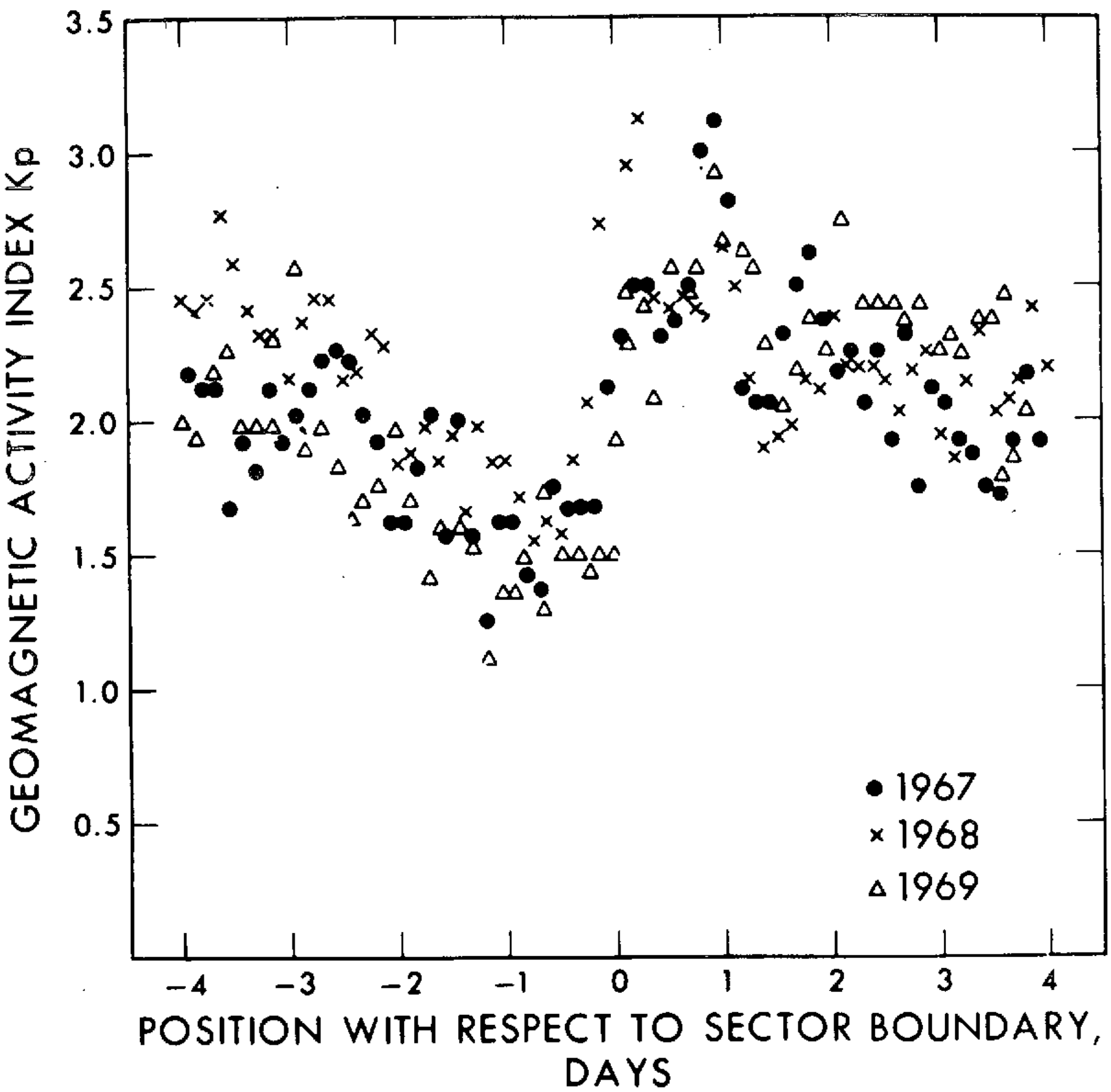

GEOMAGNETIC ACTIVITY INDEX Kp
3.5
3.0
2.5
2.0
1.5
1.0
0.5
• 1967
× 1968
△ 1969
−4
−3
−2
−1
0
1
2
3
4
POSITION WITH RESPECT TO SECTOR BOUNDARY, DAYS

**Figure 12**

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| SOLAR ACTIVITY | | | | | | |
| WEATHER | | | | | | |
| METEOROLOGICAL RESPONSE | | | | | | |

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13. ABSTRACT

The attempts during the past century to establish a connection between solar activity and the weather are discussed. Some critical remarks about the quality of much of the literature in this field are given. Several recent investigations are summarized. Use of the solar-interplanetary magnetic sector structure in future investigations is suggested to perhaps add an element of cohesiveness and interaction to these investigations.

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